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Effects of multiple cracks on the forced response of centrifugal impellers

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ABSTRACT

The effects of multiple cracks on the forced response of centrifugal impellers are investigated using a finite-element based component mode synthesis method (CMS) in this paper. The main objective is to gain some insights into the response characteristics of multiple cracked impellers and to explore efficient methods for identifying the cracks. First, in order to generate an efficient model for the nonlinear vibration analysis, a novel hybrid interface CMS method is proposed and used to conduct reduced-order modeling for the cracked impeller. Then, a method for multiple cracks modeling is developed to account for the crack breathing effects. Finally, numerical results are presented using a representative impeller with double cracks. The shifts of natural frequencies and the nonlinear forced response due to multiple cracks are of interest. Lengths and relative positions of the cracks are also considered. The results show that the natural frequencies and forced response become complexly depending on the lengths and relative positions of cracks, and the response amplitudes of blades periodically fluctuate versus blade number when an impeller suffers from cracks or mistuning. A potential method for identifying the lengths and relative positions of multiple cracks are also discussed in this paper.

1. Introduction

Cracks on key equipment are severe security risk in industrial production. The vibration of cracked structures and relevant detection techniques has been the research focus in the past decades [1–3]. Centrifugal compressors are important and widely used equipment in the steel, electric power and petrochemical industry. As centrifugal compressors advance towards high-speed and high-performance, frequent accidents due to cracks in impellers have been serious challenges for industrial applications, threatening the operation safety of the whole compressor sets. This issue has become the main concern for the reliabilities of centrifugal compressors [4–6].

In practical applications, it was found that multiple cracks frequently appeared at the weak weld joints of centrifugal impellers. Multiple cracks in impellers have received a lot of attention in turbomachinery industry. Efficient techniques for detecting the cracks have become an urgent need for the reliable operation of centrifugal compressors. However, the vibration response of multiple cracked impellers is not clear yet. Few works were reported to deal with the vibration of impellers with multiple cracks, much less to develop efficient techniques for crack detection. So, vibration analysis on

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multiple cracked impellers is conducted in this paper to gain some insights into the response characteristics and to explore efficient methods for detecting the cracks.

Most of the previous studies on multiple cracks were concerning about the vibration analysis and crack identification for beams [7–11], rotors [12–16] and pipes [17,18], which were reviewed in literature [19]. Chasalevris et al. [7] studied the dynamic behavior of a cracked beam with two transverse surface cracks and combined both response and natural frequency measurements to identify multiple cracks. Mazanoglu and Sabuncu [8] presented the flexural vibration of non-uniform Rayleigh beams with single-edge and double-edge cracks. Maghsoodi et al. [9] used a simple method to localize and quantify multiple cracks in multi-stepped beams with natural frequencies and the estimated mode shapes. Chasalevris et al. [13] investigated the coupled bending vibration of a stationary shaft with two cracks. Lin and Chu [14] studied the dynamic behavior of a rotor system with slant cracks on the shaft. In another paper of Chu [16], parametric instability of a rotor-bearing system with two breathing transverse cracks was discussed. Murigendrappa et al. [17] presented a frequency-based experimental identification method for multiple cracks in straight pipes filled with fluid. Naniwadekar et al. [18] proposed a natural frequency-based technique for crack detection by modeling the cracks in a pipe as rotational springs. However, the structural features of impellers are quite different from beams, rotors and pipes. The conclusions obtained from these structures may not be suitable to centrifugal impellers.

Regarding axial compressors, several investigations [20–25] have been conducted on the vibration response of bladed disks with a single crack using simplified or finite element-based models. Kuang et al. [20] simplified blades as Euler–Bernoulli beams and treated the crack as local disorder of the system to study the effects of local disorder on the mode localization. Hou [21] studied the mechanisms of cracking-induced mistuning in bladed disks using a lumped-mass beams model. Huang [22] used pre-twisted blades to investigate the vibration localization due to crack in a blade system. Saito et al. [24] studied the effects of mistuning and cracking on the forced response of a bladed disk. Liu and Jiang [25] presented a cracked hexahedral finite element method for dynamic analysis of cracked blades. Wang et al. [26] presented an efficient method for nonlinear vibration analysis of mistuned centrifugal impellers with crack damages and investigated the effects of mistuning and cracks on the vibration features of centrifugal impellers. However, the effects of multiple cracks have not yet been reported. Moreover, the geometry of an impeller is more complex than a bladed disk, and no simplified model is available for centrifugal impellers. Besides, the mode shapes of an impeller are mostly cover-dominated and disk-dominated, whereas the mode shapes of interest in a bladed disk are blade-dominated. So, the effects of multiple cracks on the vibration of impellers are studied in this paper.

In this paper, a hybrid interface CMS method is employed and developed to generate an efficient model for the impeller with multiple cracks. The DOFs of nodes on the multiple crack surfaces are retained in the reduced order model to simulate the crack breathing effects. Several other DOFs on the interfaces between different substructures are also regarded as fix-interface coordinates to avoid rigid body motion. The obtained nonlinear dynamic differential equations are solved by the harmonic balance method. Based on the obtained model, an impeller with double cracks is employed as representative during numerical analysis. Natural frequency shift, nonlinear forced response and vibration localization due to multiple cracks are of interest in this paper. The lengths and relative positions of double cracks are also considered to parametrically study their effects on the forced response. Mistuning effects due to manufacturing tolerance and components deterioration are also taken into account. Finally, vibration localization of the double cracked impeller is presented.

This paper is organized as follows. In Section 2, a reduced-order modeling technique for impellers with multiple cracks is presented. Section 3 contains the numerical results of the impeller with multiple cracks. In Section 4, discussions on potential method for identifying the lengths and positions of cracks are presented. Conclusions are given in Section 5.

2. Reduced-order modeling for impellers with multiple cracks

In order to accurately predict the vibration response of an impeller, the finite element model with refined mesh grids should be employed. However, the finite element model may have more than a hundred thousand DOFs. Despite of the advances in computer hardware during recent years, it is still too expensive to employ such a large model to predict the forced response directly. Thus, an order reduction method should be used to reduce the orders of the model. In this section, the formulations of the reduced-order modeling method for impellers with multiple cracks are presented. The breathing effects of multiple cracks are also taken into account using a finite-element based contact method.

2.1. Equations of motion

In the modeling process of CMS, a structure is partitioned into several substructures. Each substructure is analyzed separately to reduce the number of DOFs. An impeller consists of one cover, one disk and several blades, as is shown in Fig. 1. The finite element model and its basic sector model are shown in the figure. According to practical experience, the positions of multiple cracks are mostly located at the weld toe on the cover side of blades, as is illustrated in Fig. 1.

Due to the numerous interfaces between substructures, the single-sector finite element model is used to generate the model of the whole structure to simplify the preprocessing step. Under the Cartesian coordinate system, the overall mass and stiffness matrices of the cover, blade and disk substructures can be obtained from the matrices of their single-sector